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Investigations of the Constraints relating to Penetration of Non-Synchronous Generation (NSG) in Future Power Systems

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Abstract — According to recent projections, the installed capacity of renewable energy sources and interconnectors will increase significantly in GB power system. With such a large scale of penetration of converter-interfaced renewable energy sources and HVDC interconnectors, the existing power system, which is predominately supplied by synchronous generation presently, will face system operation challenges which are currently attracting the urgent attention of both industry and researchers. Studies have shown that the instantaneous penetration level limit of non-synchronous generation is approximately 65% in the GB power system in context of first swing angular stability and susceptible to a range of factors. There has been a lack of investigation of the individual factors and the degree to which these factors influence the non-synchronous generation limit. While the general term penetration level is often used as an annual average rather than an instantaneous operational value in many papers, it has not been fully defined or a standard definition agreed to date.

In this paper, different definitions of penetration level will be introduced and discussed. System operational issues associated with angular stability will be analysed through simulation results. It will also be illustrated that the conventional analysis method for angular stability is not applicable for future power systems with high penetration levels of NSG. Based on a simplified but high-fidelity power system model in Matlab Simulink, the penetration level limit and different factors that have the potential to influence it will be investigated and analysed. It will be shown that the angular stability limits are governed not only by the reduced system inertia, but are also influenced by factors such as system impedance and fault clearing times. Future work will be carried out to explore the penetration level limits based on GB transmission model to give more reliable results as well as to provide guidance for future requirements for generators (in particular from non-synchronous generation) to support system stability.

Keywords—*Future Energy Scenarios; NSG; Power System Stability, Voltage Source Converter; High Voltage Direct Current.*

I. INTRODUCTION

With requirements to deal with aging infrastructure and to meet environmental targets, the installed capacity of renewable energy sources (RES) and interconnectors are expected to increase to contribute a large proportion of total generation capacity. Power systems have been dominated by synchronous machines, which are electrically synchronized to system frequency. Under disturbances, synchronous machines will adjust their rotational speed spontaneously based on machine inertia and controller actions to stay in synchronism in a system. Conversely, RES and HVDC links, which are connected to the grid via power electronics, using conventional dq-axis controllers, rely on quite different mechanisms to remain synchronised with grid frequency. These converters do not contribute to system inertia, and behave as controlled current sources/sinks. They are also referred as non-synchronous generation (NSG) or converter-interfaced generation (CIG). According to [1], the total installed capacity of RES connected to the power system in Great Britain (GB) will increase from 14% in 2014 to 43% in 2035 under “Gone Green” scenario. Over a similar time period, the Scottish-English interconnector capacity is anticipated to increase by 7 GW under the “Gone Green” scenario in GB [2].

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In general, the power system is expected to transform from a relatively predictable and controllable system, to a non-synchronous and less predictable and more dynamic system [1].

This transition is expected to bring various challenges to the existing power system. As stated in [3], system strength, which is used as a measure of ability for a power system to remain stable during and following disturbances, will reduce significantly with increasing integration of NSG under future energy scenarios. The overall system inertia is one of the main factors indicative of system strength. According to [1], the overall system inertia in GB is expected to reduce by approximately 70% by 2034/35 compared to that in 2013/14, which can lead to consequences such as high rates of change of frequency (ROCOF), reduced frequency containment and system stability issues during and following disturbances [3]. Grid codes, such as those recently drafted by ENTSO-E [4][5] and National Grid (NG) [6] are critical to ensure the secure operation and reliable evolution of power systems. Grid codes typically contain information and mandate performance in terms of: time periods for NSG to remain connected during various system disturbances, reactive power supply capability and voltage and frequency control requirements.

There have been investigations into the impact of increasing penetration of RES on power system operation and stability. For example,[7][8][9][10] have proved that high levels of inverter-connected generation could affect system stability and operation – this has been proved through both mathematical analysis and simulation results.[11] and [12] investigated the voltage stability of power systems with large amounts of wind and solar PV generation. Studies in [13] have shown that the maximum NSG instantaneous penetration level (IPL) in terms of first swing stability, i.e. angular stability, is in the region of 65% of dispatched generation (MW), or 75% in terms of connected generation capacity (MVA).The individual factors and the degree to which these factors influence the NSG IPL do not appear to have been studied in detail yet.

In this paper, two different IPL definitions will be introduced and compared in section II. A simplified and representative power system model has been built to investigate system stability under different penetration levels of NSG, and this model is introduced in section III. Stability issues, especially related to angular stability, associated with increasing penetration of NSG and factors that influence the IPL limit will be investigated using simulation tests in Matlab SimPowerSystems in section IV. Simulation results and discussions on requirements from NSG to support system stability are presented in section IV. Conclusions are summarised in section V.

II. PENETRATION LEVEL DEFINITIONS

Many researchers and industrialists have been involved in debate relating to the generation mix and levels of NSGs under future energy scenarios and the possible impacts that this will have on the overall power system. When referring to IPL of RES and interconnectors, different definitions are sometimes used. In this section, two IPL definitions are presented. Note that more definitions are possible, e.g. including the percentage of linear and non-linear loads, etc. and only basic definitions are summarised in this paper.

A. *Definition 1*

A basic definition of NSG IPL (IPL_1) [14][15] is simply the ratio of dispatched generation P_{NSG} from NSG to total demand P_{Demand} in the system, as shown in (1). This definition presents an intuitive indication of the percentage of overall generation that is supplied from NSG for a certain amount of demand. However, the dispatched generation is not usually used by the system operators and manufacturers for system performance forecasting since it is an instantaneous value of output power from certain combinations of generation sources.

$$IPL_1 = \frac{P_{NSG}}{P_{Demand}} \times 100\% \qquad (1)$$

Meanwhile [13] considers a definition that takes account of the imported power into GB via HVDC links P_{HVDC_import} as part of the total NSG on the system and the exported power from GB via HVDC links P_{HVDC_export} asan element of total system demand, as shown in (2). However, it is not totally clear whether *P* in this definition represents MW or MVA ratings of plant or the actual dispatched power from the generators. Generally, the capacity factor of RES is lower, i.e. an average of 30% or lower [16][17], compared with an average of 80%~90% for synchronous generation [18]. This can make the

NSG ratings (particularly if *P* represents MW/MVA ratings) to be very high values and therefore, the definition of IPL_1 can easily exceed 100% in many cases.

$$IPL_1 = \frac{P_{NSG} + P_{HVDC\_Import}}{P_{Demand} + P_{HVDC\_Export}} \times 100\% \quad (2)$$

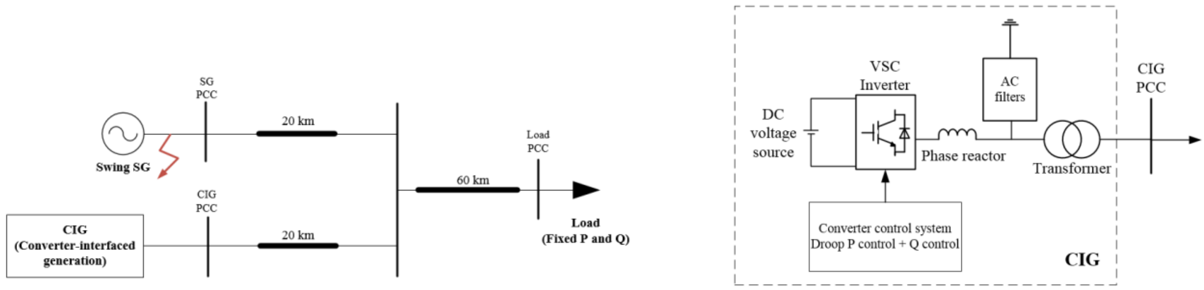
B. Definition 2

Since manufacturers and system operators normally use the rated values system equipment in system planning and forecasting applications, another definition for IPL can be defined as shown in (3), where S_{NSG} represents the total MVA rating, i.e. the full ratings, of all NSGs including RES and HVDC interconnectors and S_{System} represents the total system MVA ratings which is the summation of all synchronous and non-synchronous generation on the system. This definition is more suited to representing IPLs and IPL limits within an arguable more sensible range, i.e. 0~100%. Since all definitions of IPL should be standardised and applicable in different studies, definition IPL_2 will be used in this paper.

$$IPL_2 = \frac{S_{NSG}}{S_{System}} \times 100\% \quad (3)$$

III. DESCRIPTION OF THE TEST SYSTEM

A simplified power system model has been built with a combination of SG and NSG supplying the load. The ratio of NSG to SG can be varied. This simplified test system may not be capable of assessing accurately IPL limits in practical power systems due to the lack of detail, but it is sufficient for the studies being reported here (and will be replaced with actual system model at a later stage in this project). However, the relatively high fidelity reduced model has been achieved through detailed transient modelling and the use of small sampling time step (i.e. 0.5ms for NSG control system and 0.05ms for the test system). Also, general IPL limits and how they are influenced by various parameters and disturbances should be similar whether a reduced or full-size power system model is used.



(a) (b)

Figure 1. (a) Configuration of test system consisting of a swing SG, CIG model, load and transmission lines; (b) Configuration of CIG in the test system

The simplified test system is shown in Figure 1(a) and parameters of the system are included in the appendix. In the model, each generator is connected using relatively short transmission lines, built using series RLs circuit with variable line lengths. The load in the system is represented by a three-phase parallel RL load with fixed impedance. A standard synchronous machine model from the Simulink library has been utilised for the swing SG, which operates at minimum loading at 60%. The control system of the SG consists of a typical active power-frequency droop governor combined with a prime mover and a discrete excitation system having an IEEE type 1 synchronous machine voltage regulator combined with an exciter. A CIG model is designed to form the inverter side of voltage source converter (VSC) based HVDC transmission system, which is then connected to a DC bus to represent the rectifier side with assumption of a constant and well-controlled DC link voltage, as shown in Figure 1(b). This CIG model can represent various types of NSGs and HVDC interconnectors. Control system of the CIG model implements the conventional active and reactive power control of VSC-HVDC system. An additional frequency-active power droop control is applied to enable CIG to have the capability to cooperate with the rest of the system by adjusting its active power setpoint according to grid frequency variation; otherwise the system will not be able to settle down. Capacity factor of the CIG is set at 30%, which is an average level of NSG [16][17].

The simplified system has been tested and validated by comparing the dynamic response with PMU-recorded data of a frequency-drop event in GB power system which occurred on the 30th September 2012. The system performance in terms of frequency and ROCOF response is consistent with the recorded data.

IV. Simulation results and discussion

Based on the validated simplified test system, the IPL limit in terms of angular stability can be investigated by varying the proportion of generation contributed from the SG and CIG respectively. Definition PL_2 defined by equation (3) will be used in this paper with P_{HVDC_Import} and P_{HVDC_Export} set to zero. Various tests have been carried out to explore the IPL limit in terms of steady-state and transient angular stability and also the factors that influence the IPL limit. To facilitate comparative analysis, a base case is set up as described in the appendix. The values of SG inertia constant and transmission line length are selected as factors to be investigated. Note that the IPL limit may vary under different system settings, architectures and configurations, but the trend of IPL limit against different factors should be similar, and thus, the results should be very informative.

The conventional analysis method for angular stability is based on the equal area criterion and the mechanisms of a synchronous machine [19]. This analysis method is only really applicable within systems containing an infinite/slack bus or a very string “backbone” of high-inertia synchronous machines. However, for future power systems under scenarios of high IPL of NSG, the “backbone” of high-inertia machines is significantly reduced, and the system cannot be considered to have an infinite or slack bus at any point. Therefore, use of the equal-area criteria to assess stability of the remaining SG machines in future power networks may not to be appropriate. Therefore, rather than measuring rotor angles of the synchronous generation, voltage phase angles between the generator terminals are measured as an indicator to angular stability in this paper. Instability can be “detected” by looking for excessive angular differences or even rotations similar to “pole slipping”, or by observing high-frequency or sub-synchronous oscillations in the phase angles. In many cases, when instability occurs at high IPLs of NGS, instability can also be detected by similar deviations in the Phased-Locked-Loops (PLLs) or instantaneous power outputs of the converters. When instability occurs, waveform (current) power quality from the converters can decay rapidly, with subsequent deviations also in voltage power quality, in a closed-loop fashion. Net active power output from the NSGs can decay rapidly during instability, while instantaneous power output becomes oscillatory, in a manner not dissimilar to “pole slipping”, but with additional harmonic and inter-harmonic effects.

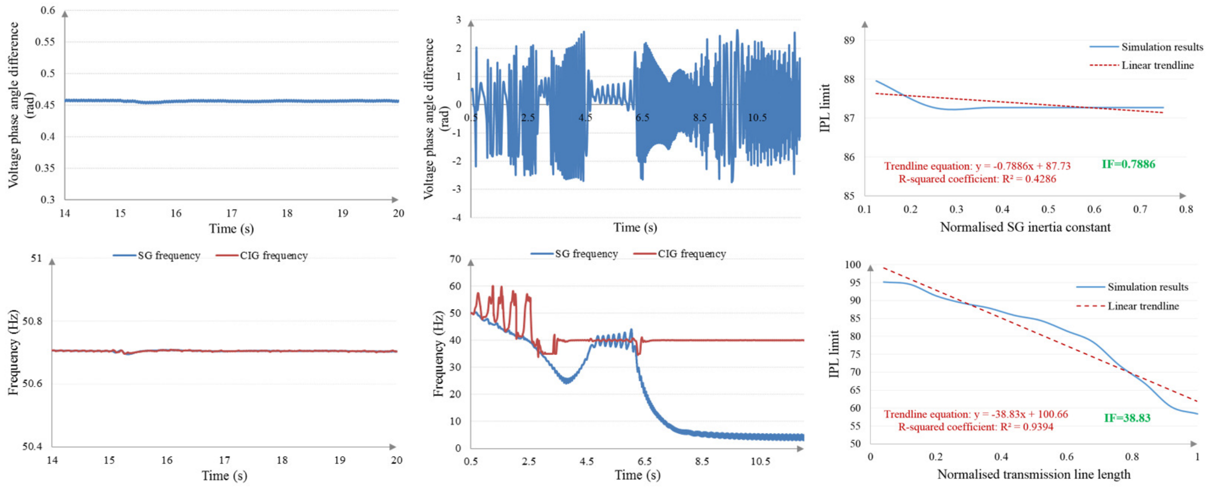
A. Steady-state stability

Using the test system shown in Figure 1, the steady-state stability has been investigated at different levels of NSG by applying a small disturbance in a form of a load step change (3% of the total demand) at 15s. Under lower IPL, e.g. 53% as shown in Figure 2(a), both frequency and voltage phase angle difference between SG and CIG indicate that after the load step change the system settles down quickly into a steady-state condition. However, when the IPL of NSG increases to a certain high level, the system can no longer reach a stable condition. An example response at the penetration level of 91% is shown in Figure 2(b). Voltage phase angle difference between the SG and CIG continually oscillates and the system never reaches a stable condition. This is also confirmed on the frequency trace (measured at generation point of common couplings) presented in Figure 2(b) where the loss of stability is self-evident. Therefore, under IPL of 91% the frequencies of SG and CIG are different indicating loss of synchronism in the system. Since the CIG is well-controlled with frequency-active power droop control, the CIG should be able to maintain the load. However, the instability of the converter under high IPLs, where they are not able to effectively output active power, as shown in Figure 3(a), resulting imbalance of power in the network and therefore system instability. Meanwhile, the control system of CIG has become seriously unstable as seen from the dq-axis currents (i_d and i_q) in the converter control system shown in Figure 3(b), while they are well controlled under low IPLs. The IPL limit in the test system in terms for steady-state stability is found to be 87% for the base case.

Two factors, system inertia and system reactance (which is a sum of the generator and transmission system reactance), are considered in this paper. Their effect on impact on the IPL limit has been investigated and is presented in Figure 2(c). In order to analyse the degree of impact of each factor, the slope of linear trendline of simulated results has been chosen as the indicator, which for the purposes of this publication has been termed as the impact factor (IF). Also, the R2 value is shown to indicate the fitness of linear interpolation. To enable comparative analysis of the two physically different influencing factors both the inertia constant and total transmission line length have been normalised into 0-1 range, considering realistic minimum and maximum values encountered in the transmission system. These were assumed as 2s-10s for inertia constant and 0km-100km for the transmission line length. Corresponding relationships between the actual values and normalised values are included in the appendix.

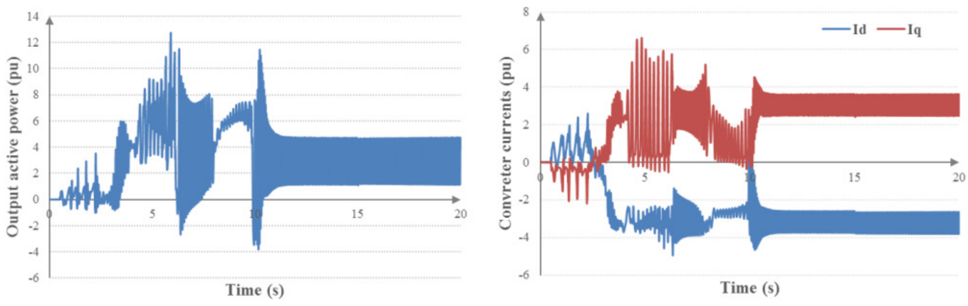
In terms of steady-state angular stability, it has been found that, when system inertia increases the IPL limit is initially slightly reduced (i.e. 1% between 3s to 4s) but overall has very little influence on the penetration level limit. The IF for system inertia on IPL limit is only 0.79. For system reactance investigation, total transmission line length between SG and CIG was varied. As shown in Figure 2(c), the IPL limit drops from 95% to 58% with transmission line length increasing from 4 km to 100 km. In this case IF=38.83. As discussed before, under high IPL of NSG, the converter outputs can degrade substantially (and suddenly) when the “tipping point” threshold is crossed, which leads to instability of the whole system. With increasing system reactance, the dq-axis currents from the CIG control system create a larger voltage deviation at the terminals of the CIG, and the system is more liable to become unstable.

Comparing the IF values for inertia constant and for total transmission line length, it is obvious that the system reactance has a much higher effect on the IPL limit when it comes to steady-state angular stability. Besides, the R^2 value of the trendlines shown in Figure 2(c) indicate that the relationship of system reactance versus IPL limit is much more linear than that of the system inertia.



(a) System response with IPL=53% (b) System response with IPL=91% (c) effects of system inertia and reactance on IPL limit

Figure 2. Steady-state system responses (frequency and voltage phase angle difference) under different IPLs and investigation on factors that influencing the IPL limit in terms of steady-state stability



(a) (b)

Figure 3. CIG responses under IPL=91%: (a) output active power from the CIG and (b) dq-axis currents in the control system of CIG

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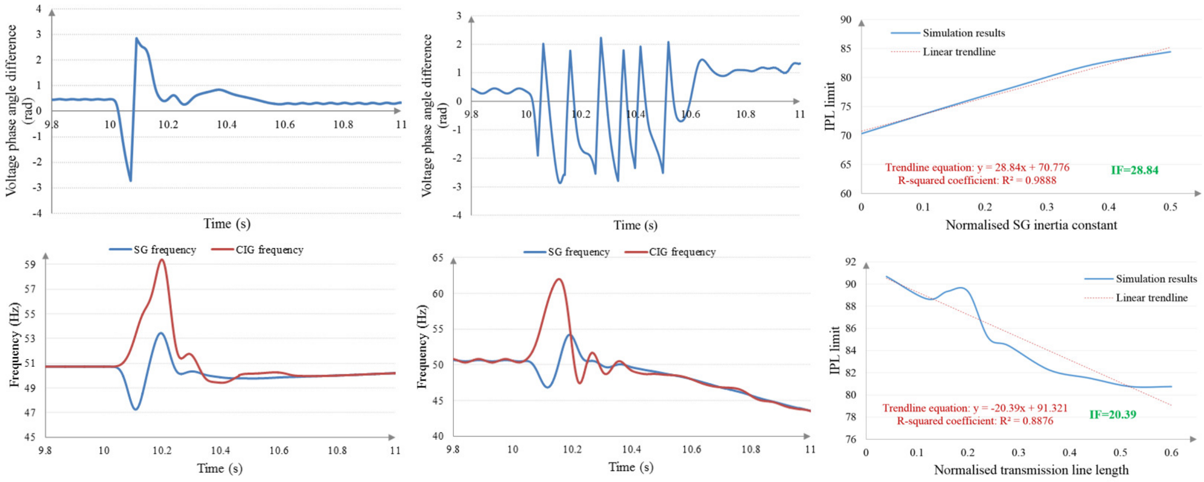
B. Transient stability



(a) System response with IPL=53% (b) System response with IPL=87% (c) effects of system inertia and reactance on IPL limits

Figure 4. Transient system responses (frequency and voltage phase difference) under different IPLs and investigation on factors that influencing the IPL limits in terms of transient stability

To access transient stability, a balanced three-phase solid fault is applied at the SG, which is considered to be the worst case in the test system. Fault clearing time is set to 100ms, which is the standard expected clearance time at the transmission level in GB. Under the fixed clearance time, the transient angular stability has been investigated, as shown in Figure 4. Under lower IPL, i.e. 53%, the transient frequency and voltage phase angle response initially show spikes after the fault inception but the stability is restored afterwards. However, at certain penetration level, e.g. 87% as shown in Figure 4(b), the voltage phase angle difference cannot get back to a steady level, and frequencies of both SG and CIG continue dropping after the fault clearance, i.e. transient instability occurs. The IPL limit in terms of transient angular stability has been established at 82%. Compared to 87% IPL limit in terms of steady-state stability, the stability limit in terms of transient stability is lower. This is to be expected due to exposure to a much bigger disturbance.

As shown in Figure 4(c), with increasing system inertia, the IPL limit in terms of transient stability increases significantly with IF=28.84. Meanwhile, system reactance also influences the IPL limit which is shown in Figure 4(c). The IPL limit in terms of transient angular stability decreases with increasing system reactance, with IF=20.39. Therefore, for transient angular stability, both system inertia and system reactance have significant effects on the IPL limit, while system inertia has proved to have higher degree of effect. To improve transient stability, system inertia should be high enough to support the system stability. For NSGs which inherently do not contribute to system inertia, control technologies to enable them to provide synthetic inertia are important for system enhancement under future energy scenarios.

Additionally, from the R^2 value of the two relationships, it can be seen that the relationship between system inertia and the IPL limit fits the linear trendline well, while that of the system reactance is less linear.

C. Requirements from NSG to support system stability

The IPL limits in terms of steady-state and transient angular stability are 87% and 82% respectively, based on base case in the test system. The system inertia and total reactance between the generators have both demonstrated to have an effect on the IPL limit.

It is advantageous for a power system to have a low system reactance at a low and acceptable range related to system ratings, to maintain angular stability and enhance system strength. However, this value is difficult to estimate for a real power system due to the complex system architecture, as well as configuration and variable generation and load.

For transient stability, it is important to keep the system inertia above a minimum value to ensure system stability with increasing penetration of NSG. There have been investigations on inertia provision in NSGs to support the system stability, for example, paper [20] has proposed an inertia emulation control scheme based on VSC-HVDC transmission system, which has been proved to have the capability to improve system frequency and angular stability. The concept “virtual synchronous machine (VSM)” has been widely investigated which mimics the behaviour of a SG on a converter interface, i.e. both electrical and dynamic parts of a SG, such as the “VISMA” concept [21][22], “synchronverter” concept [23][24][25], and others. To ensure a stable and reliable operation of the future power systems, control systems of NSG should be able to provide certain amount of synthetic inertia [26].

The fault clearing time is important to ensure system transient stability. With shorter fault clearing time, the system will become more stable and the transient stability can be improved. However, to reduce the fault clearing time involves considerable work (as well as cost) due the limits imposed by time delays in communications, fault detection devices and relays, circuit breaker operating times, etc. Improved protection schemes may be required in the future power systems to ensure system stability [27].

V. Conclusions

In this paper, future power system scenarios and issues under such scenarios have been introduced, especially for GB power system. Two types of IPL definitions have been introduced and discussed. Angular stability issues under increasing penetration of NSG and factors that have the potential to influence the IPL limit have been discussed and investigated using dynamic simulation. A high-fidelity simplified power system model has been built in Matlab Simulink to explore the IPL limits. A concept, impact factor, has been introduced and used in this paper as an indicator of the degree of influence. It has been proven that both system inertia and system reactance have the effects on IPL limits. While system reactance influences more the steady-state angular stability and system inertia influences both the steady-state and transient angular stability significantly. Also, the simulation results of effects of selected factors have been analysed with R^2 value of their linear trendlines to show their fittings in linearity relationship. Furthermore, requirements from NSG to support power system stability have been discussed and summarised.

Even though the values of IPL limits obtained in this paper do not accurately reflect the real situation in the GB power system due to the use of simplified model, the fact that there are limits in terms of angular stability and trends of different factors influence the IPL limits are a very useful indicator and guideline for future more detailed analysis using larger equivalent transmission system model.

Future work will be focused on the following aspects:

- Investigation of additional factors that have the potential to influence the IPL limits, e.g. fault clearing time, converter control delay time, PID gains in the inner current controller of the converter and move away from phase locked loop (PLL) based controllers.
- Investigation of different converter control strategies that have the potential to improve the system strength, e.g. synthetic inertia control with focus on adding synchronising torque.

Investigation of the IPL limits using larger equivalent impacting GB transmission model in DIgSILENT PowerFactory for further validation of the results as well as guidance for future requirements from generation (in particular NSG) to support system stability.

VI. Appendix

AC TRANSMISSION LINES		CIG	
Model	Three-phase series RL branch	Rated ac voltage V_{AC}	230kV
Resistance per unit length	$0.04\ \Omega/\text{km}$	Nominal dc voltage V_{dc}	$\pm 100\text{kV}\ (200\text{kV})$
Inductance per unit length	$1.273\text{e}-3\ \text{H/km}$	Transformer turns ratio	$230/100\ \text{kV}$
X/R ratio	8	Reactor resistance	$0.0015\ \text{pu}$
SG line length (Base case)	20 km	Reactor inductance	$0.1\ \text{pu}$
CIG line length (Base case)	20 km	Rated ac voltage V_{AC}	230kV
Load line length (Base case)	60 km	Nominal dc voltage V_{dc}	$\pm 100\text{kV}\ (200\text{kV})$
SYNCHRONOUS GENERATOR			
Rated Voltage	$230\ \text{kV}$	REACTANCE x_d, x'_d, x''_d	$1.305, 0.296, 0.252\ \text{pu}$

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Inertia H (Base case)	5 s	REACTANCE x_q, x_q'', x_1	0.474, 0.243, 0.18 pu
Minimum loading	60%	TIME CONSTANTS $\tau_d', \tau_d'', \tau_q''$	4.49, 0.0681, 0.0513 s
LOAD		**BALANCED THREE-PHASE FAULT**	
Nominal voltage	230 kV	Fault resistance R_{on}	0.0001 Ω
Active power, Reactive power	1.15 GW, 162 MVar	Fault resistance R_g	0.0001 Ω
Power factor	0.99	Fault clearing time	100 ms
Load step	0.03	**RELATIONSHIP OF REAL VALUES AND STANDARDISED VALUES**	
SYSTEM SETTINGS			
System sampling time	$5e^{-5}$ s	Inertia constant	[2, 3, 4, 5, 6, 7, 8, 9, 10] s
Nominal frequency	50 Hz	Standardised inertia constant	[0, 0.125, 0.25, 0.375, 0.5, 0.625, 0.75, 0.875, 1]
Rated voltage	230 kV	Total transmission line length	[0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100] km
Simulation time	20 s	Standardised transmission line length	[0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1]

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